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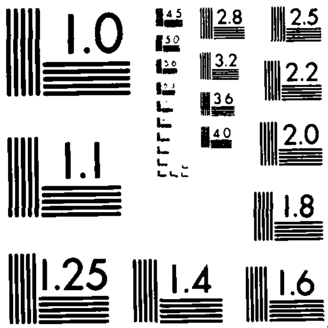

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PREDICTION OF IMPACT PRESSURE INDUCED BY BREAKING WAVES ON MARINE SYSTEMS IN RANDOM SEAS

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PREDICTION OF IMPACT PRESSURE INDUCED BY BREAKING WAVES
ON MARINE SYSTEMS IN RANDOM SEAS

by

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A method to statistically predict the magnitude of impact pressure (including extreme values) produced by deep water waves breaking on a circular cylinder is developed. The probability density function of impact pressure associated with breaking waves is derived for a specified wave spectrum. As an example of the application of the present method, numerical computations are carried out for a wave spectrum obtained from measured data in the North Atlantic.

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ABSTRACT

This paper presents a method to statistically predict the magnitude of impact pressure (including extreme values) produced by deep water waves breaking on a circular cylinder representing a column of an ocean structure. Breaking waves defined here are not those whose tops are blown off by the wind but those whose breaking is associated with steepness. The probability density function of wave period associated with breaking waves is derived for a specified wave spectrum, and then converted to the probability density function of impact pressure. Impacts caused by two different breaking conditions are considered; one is the impact associated with waves breaking in close proximity to the column, the other is an impact caused by waves approaching the column after they have broken. As an example of the application of the present method, numerical computations are carried out for a wave spectrum obtained from measured data in the North Atlantic.

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INTRODUCTION

Recent progress in the stochastic processes approach to ocean engineering permits fairly accurate estimation of wave-induced loadings on marine systems required for design and safe operation.

One type of wave-induced loading which is comparatively little known and with which the present study is primarily concerned, is that associated with breaking waves in deep water. Breaking waves defined here are not those whose tops are blown off by the wind but those whose breaking is associated with steepness. These breaking waves exert by far the largest wave-induced force (often in the form of impacts) on marine systems, which may cause serious safety problems and structural damage of the system. Kjeldsen and Myrhaug (1979) have shown an example of measured impact pressure caused by breaking waves generated in the tank.

Although many studies have been carried out on impacts on coastal structures associated with breaking waves in shallow water, there exists as yet very little information on impacts on marine structures caused by breaking waves in deep water. In particular, no study has been made to date to statistically predict the magnitude of impact pressure.

This paper presents a method to evaluate the magnitude of impact pressure (including extreme values) expected to occur on the front face of a circular cylinder associated with breaking waves in a sea having a specified wave spectrum. In the present study the waves are assumed to be a Gaussian random process with

non-narrow-band-spectrum. This implies that the waves may have more than one peak during a half-cycle determined from successive zero-crossings, and hence wave breaking which takes place along an excursion above the zero-line as well as that which occurs along an excursion crossing the zero-line are considered. This will be explained in detail later in connection with Figure 4. The frequency of occurrence of breaking waves under these two different situations in a given sea (wave spectrum) was studied earlier by the authors (Ochi and Tsai 1983), and the results are applied to the present study.

The following steps are taken in the derivation of the probability function necessary for predicting impact pressure caused by waves breaking on a circular cylinder which is considered to represent a column of an offshore structure:

(a) The joint probability density function of excursion (wave height) and time interval (period) are obtained for a given wave spectrum. From this joint probability density function, the probability density function of period associated with breaking waves is derived taking the breaking criterion into consideration.

(b) Functional relationships between pressure, wave particle velocity, and wave celerity at the instant breaking waves impact a circular cylinder are obtained through experiments in waves generated in the tank. Then, the relationship between impact pressure and breaking wave period is derived.

(c) From Items (a) and (b), the probability density function of periods associated with wave breaking is converted to that of impact pressure by applying the techniques of transformation of random variables.

Furthermore, the magnitude of extreme impact pressure expected to occur in a specified time period in a given sea (wave spectrum) is estimated by applying order statistics.

HYDRODYNAMIC IMPACT ASSOCIATED WITH BREAKING WAVES

Prior to developing a method to predict the magnitude of impact pressure on a marine structure caused by breaking waves, it may be well to give a brief description of the wave breaking phenomenon in deep water. Longuet-Higgins (1975) has shown that some characteristics of deep water gravity waves (such as speed, energy, etc.) increase monotonically with increase in wave amplitude up to a certain magnitude and then diminish before the wave reaches its maximum amplitude, the magnitude of which depends on wave length. The fluid particle velocity at the wave crest moves forward with a speed less than the phase speed (wave celerity), in general; however, these two velocities become equal when the wave attains its maximum amplitude. The exceedance of the particle velocity over the phase speed results in an ejection of a fluid jet from the crest and breaking will take place. Cokelet (1977) has shown that the phase speed of waves for which breaking is imminent is 1.092 times that given by linear wave theory.

As noted in the Introduction, breaking waves exert by far the largest wave-induced force on marine systems. The wave-induced pressure on a circular column of an offshore structure may

be approximately equal to the hydrostatic pressure associated with wave elevation at any instant of time. However, when the column encounters breaking waves, the pressure on the column rises very rapidly in the form of an impact of short duration, followed by another pressure increase due to the passage of the breaking waves. Although the magnitude of impact pressure varies depending on the vertical position of the breaking waves, the highest pressure is expected to occur at the crest level of the breaking waves.

In evaluating the magnitude of impact pressure on a marine system associated with breaking waves, impacts caused by two different breaking conditions are considered. One is the impact associated with waves breaking in close proximity to the structure, the other is an impact caused by waves approaching the structure after they have broken. These impacts are called *breaking wave impact* and *broken wave impact*, respectively, (see Figure 1) in the present paper. This consideration is necessary to clarify the pressure-velocity relationship as well as the (particle) velocity-wave celerity relationship, both of which are required for evaluating impact pressure magnitude from a knowledge of the wave period (length). These relationships are different for the breaking wave impact and for the broken wave impact as presented below.

In order to clarify the functional relationship between the magnitude of impact pressure and fluid partical velocity at the instant of a breaking wave impacts a structure (hereafter referred to as impact velocity), an experimental study was carried out by

generating breaking waves in the 40-meter long wave tank at the University of Florida. During the tests, impact pressure was measured at the front face of a circular cylinder fixed vertically in a seaway. The details of the experiments are outlined in the Appendix I.

Figure 2 shows impact pressure, p, as a function of impact velocity, u, for both breaking wave impact and broken wave impact. Included also in the figure are lines drawn through the average of the measured data. As can be seen in the figure, the pressure associated with breaking wave impact is much greater than that associated with broken wave impact for the same impact velocity. However, for both types of impact, impact pressure is proportional to the square of impact velocity. That is,

$$p = k\, u^2 \tag{1}$$

where, p = impact pressure in kg/cm^2

u = impact velocity in m/sec.

and k is a constant given by,

$$k = \begin{cases} 6.1 \times 10^{-6}\ \text{kg-sec}^2 & \text{for breaking wave impact} \\ 2.8 \times 10^{-6}\ \text{kg-sec}^2 & \text{for broken wave impact} \end{cases}$$

Next, impact velocity will be expressed as a function of celerity (phase velocity) of the incident wave associated with either the breaking or broken wave impact. For this, measured impact velocities, u, are plotted as a function of the measured celerities, C_*, and the results are presented in Figure 3. It can be seen in the figure that impact velocity for the breaking wave

impact is less than that for the broken wave impact when the wave celerities are the same. However, impact velocity is approximately linearly proportional to wave celerity for both breaking and broken wave impacts. That is,

$$u = \theta C_* \tag{2}$$

where, C_* = wave celerity

and θ is a constant given by,

$$\theta = \begin{cases} 0.48 \text{ for breaking wave impact} \\ 0.70 \text{ for broken wave impact} \end{cases}$$

Furthermore, in order to express impact pressure as a function of incidental wave period, it is assumed that the wave celerity, C_*, associated with wave breaking is equal to 1.092 times that evaluated from linear wave theory (Cokelet 1977). That is,

$$C_* = 1.092\left(\frac{gT}{2\pi}\right) \tag{3}$$

where, g = gravity constant

T = wave period

Thus, from Equations (1) through (3), the following functional relationship between impact pressure and wave period can be derived:

$$p = k\theta^2\left(1.092\,\frac{gT}{2\pi}\right)^2 \tag{4}$$

$$\text{where,} \quad k\theta^2 = \begin{cases} 1.41 \times 10^{-6} & \text{for breaking wave impact} \\ 1.37 \times 10^{-6} & \text{for broken wave impact} \end{cases}$$

It is recalled that the k-value is greater for breaking wave impact than that for broken wave impact for the same impacting velocity; however, the trend is reversed for the θ-value for the same wave celerity. This results in the magnitudes of impact pressure for a given wave period being nearly equal for breaking wave impact and for broken wave impact. This conclusion simplifies significantly the procedure for statistically evaluating the magnitude of impact pressure associated with wave breaking, since it is not necessary to evaluate separately the probability of occurrence of breaking wave impact and broken wave impact on a structure.

PREDICTION OF MAGNITUDE OF IMPACT PRESSURE

The magnitude of impact pressure (including that of the extreme pressure) on a marine system caused by breaking waves in random seas will be statistically evaluated from a knowledge of the wave spectrum. This can be achieved by using the functional relationship between impact pressure and wave period derived in Equation (4) in the previous section in conjunction with the probability density function of wave period. It should be noted, however, that the probability density function of wave period is not that for periods of all waves in a given sea but for periods

associated with breaking waves only. Therefore, it is necessary to derive the probability density function of " breaking wave period" from the joint probability density function of wave height and period taking the wave breaking criterion into consideration. In order to elaborate this, the following discussion is given:

In evaluating the frequency of occurrence of breaking waves in severe seas, it is highly desirable to consider the waves to be a non-narrow-band random process, and to consider breaking which occurs under two different situations; one which takes place along an excursion above the zero-line (Type II excursion), the other which occurs along an excursion crossing the zero-line (Type I excursion) as illustrated in Figure 4. For each type of excursion, the joint probability density function of an excursion (height) and associated time interval (period) are computed for a given spectrum as shown in the example demonstrated in Figure 5 (Ochi and Tsai 1983). Here, the excursion and time interval are expressed in dimensionless form. Included also in the figure is the line indicating the breaking criterion in dimensionless form which is given by,

$$\nu \geq \alpha \left(\frac{\overline{T}_m^{\,2}}{\sqrt{m_o}} \right) \lambda^2 \tag{5}$$

where, ν = dimensionless excursion = $\zeta / \sqrt{m_o}$

λ = dimensionless time interval between positive maxima = $T/\overline{T}_m$

ζ = excursion

T = time interval between positive maxima

$\bar{T}_m$ = average time interval between successive positive maxima A

$$= 4\pi \left(\frac{\sqrt{1 - \varepsilon^2}}{1 + \sqrt{1 - \varepsilon^2}} \right) \sqrt{\frac{m_o}{m_2}}$$

ε = band-width parameter of the spectrum = $\sqrt{1 - \frac{m_2^2}{m_0 m_4}}$

m_j = j-th moment of the wave spectral density function

α = 0.196 for m-sec-units

Wave breaking takes place in the region where the wave excursion exceeds the criterion line which is identified as the "breaking zone"in Figure 5. The probability density function of wave period to which Equation (4) is applied is the marginal density function of wave period within the breaking zone shown in the figure. The analytical procedure for evaluating the probability density function of breaking wave period is as follows:

Let $f_I(\nu,\lambda)$ and $f_{II}(\nu,\lambda)$ be the joint probability density functions of excursion and time interval (in dimensionless form) for Type I and Type II excursions, respectively, shown in Figure 4. The formulations $f_I(\nu,\lambda)$ and $f_{II}(\nu,\lambda)$ are transcribed from Ochi and Tsai (1983) and are given in Appendix II. Since breaking during both Type I and Type II excursions is considered, these joint probability density functions are combined with the frequencies of occurrence for each type of excursion. It is noted, however, that care must be taken when combining Type I joint probability density function with Type II density

function. Type I probability density function, $f_I(\nu,\lambda)$, is essentially the joint probability density function of the positive maxima (the height of Point A above the base-line in Figure 4) and the associated time interval. Hence, it includes a portion of the positive maxima which also belongs to Type II excursion. Taking into consideration the elimination of this overlap portion in the probability density function, the combined joint probability density function of excursion and period is given by,

$$f(\nu,\lambda) = \frac{p_I^2 f_I(\nu,\lambda) + p_{II} f_{II}(\nu,\lambda)}{\int_0^\infty\int_0^\infty \{ p_I^2 f_I(\nu,\lambda) + p_{II} f_{II}(\nu,\lambda)\}\, d\nu d\lambda} \tag{6}$$

where $f_I(\nu,\lambda)$ = joint probability density function of positive maxima (double amplitudes) and associated time interval (period) including that applicable to Type I excursion (see Appendix II)

$f_{II}(\nu,\lambda)$ = joint probability density function of excursion (height) and associated time interval (period) of Type II excursion

p_I = frequency of occurrence of Type I excursion

$$= \frac{2\sqrt{1-\varepsilon^2}}{1+\sqrt{1-\varepsilon^2}}$$

p_{II} = frequency of occurrence of Type II excursion

$$= \frac{1-\sqrt{1-\varepsilon^2}}{1+\sqrt{1-\varepsilon^2}}$$

From the breaking criterion given in Equation (5), the truncated joint probability density function in the breaking zone, denoted by $f_*(\nu,\lambda)$, can be evaluated as,

$$f_*(\nu,\lambda) = \frac{f(\nu,\lambda)}{\displaystyle\int_0^{\infty}\int_{\alpha\left(\frac{\bar{T}_m^2}{\sqrt{m_o}}\right)\lambda^2}^{\infty} f(\nu,\lambda)\, d\nu d\lambda} \tag{7}$$

$$\alpha\left(\frac{\bar{T}_m^2}{\sqrt{m_o}}\right)\lambda^2 < \nu < \infty, \quad 0 \leqq \lambda < \infty$$

Then, the probability density function of breaking wave period (in dimensionless form), denoted by $f_*(\lambda)$, can be obtained as the marginal density function of Equation (7) and Equation (6). That is,

$$f_*(\lambda) = \int_{0\,\alpha\left(\frac{\bar{T}_m^2}{\sqrt{m_o}}\right)\lambda^2}^{\infty} f_*(\nu,\lambda)\, d\nu$$

$$= \frac{\displaystyle\int_{\alpha\left(\frac{\bar{T}_m^2}{\sqrt{m_o}}\right)\lambda^2}^{\infty} f(\nu,\lambda)d\nu}{\displaystyle\int_0^{\infty}\int_{\alpha\left(\frac{\bar{T}_m^2}{\sqrt{m_o}}\right)\lambda^2}^{\infty} f(\nu,\lambda)d\nu d\lambda}$$

$$= \frac{\displaystyle\int_{\alpha\left(\frac{\bar{T}_m^2}{\sqrt{m_o}}\right)\lambda^2}^{\infty} \{p_I^2 f_I(\nu,\lambda) + p_{II} f_{II}(\nu,\lambda)\}d\nu}{\displaystyle\int_0^{\infty}\int_{\alpha\left(\frac{\bar{T}_m^2}{\sqrt{m_o}}\right)\lambda^2}^{\infty} \{p_I^2 f_I(\nu,\lambda) + p_{II} f_{II}(\nu,\lambda)\} d\nu d\lambda} \tag{8}$$

Note that the denominator of the above equation is simply the probability of occurrence of breaking waves for a given wave spectrum.

Next, the functional relationship between impact pressure and wave period given in Equation (4) is expressed in terms of the dimensionless wave period, λ. That is,

$$p = k\theta^2 \left(1.092 \frac{g\bar{T}_m}{2\pi}\right)^2 \lambda^2 = \phi\lambda^2 \tag{9}$$

where $\phi = k\theta^2\left(1.092 \frac{g\bar{T}_m}{2\pi}\right)^2$

From Equations (8) and (9), the probability density function of impact pressure can be derived by applying the technique of transformation of random variables. That is,

$$f(p) = \left| f_*(\lambda) \right|_{\lambda = \sqrt{p/\phi}} \cdot \left|\frac{d\lambda}{d\phi}\right| \tag{10}$$

where $\quad \left|\frac{d\lambda}{dp}\right| = 1/(2\sqrt{p\phi})$

Various statistical information on impact pressure on a circular cylinder caused by breaking waves can be obtained from Equation (10). Among others, the estimation of the magnitude of the largest impact pressure (extreme pressure) expected to occur in a specified number of breaking waves or in a specified time period will provide information vital to the design of marine systems.

The probability density function applicable to extreme pressure in n-wave breakings, denoted by $g(p_n)$, can be obtained by applying order statistics to Equation (10). That is,

$$g(p_n) = n \left| f(p)\{F(p)\}^{n-1} \right|_{p=p_n} \tag{11}$$

where, $\quad n$ = number of wave breakings

$F(p)$ = cumulative distribution function of pressure

$= \int_o^p f(p)dp$

The probable extreme pressure, denoted by $\bar{p}_n$, is defined as the modal value of the probability density function, $g(p_n)$, and is that which is most likely to occur in n-wave breakings. It is given as the solution which satisfies the following condition:

$$\frac{d}{dp_n} g(p_n) = 0 \qquad (12)$$

Since the probable extreme pressure obtained from the above equation is a function of the number of breaking waves, it will be much more useful and practical if the magnitude of extreme pressure is given as a function of time in a given sea (wave spectrum). This can be done from information on the expected number of wave breakings in a specified period of time. The probability of occurrence of breaking waves is given as the denominator of Equation (8). On the other hand, the average time interval between successive positive maxima, denoted by $\bar{T}_m$, is given in Equation (5). By using these results, the number of wave breakings expected in T_h-hours (specified) for a given wave spectrum can be evaluated as follows:

$$n = \Pr\left\{\text{Breaking waves}\right\}\left(\frac{T_h}{\bar{T}_m}\right) \times (60)^2$$

$$= \frac{1}{4\pi}\left(\frac{1+\sqrt{1-\varepsilon^2}}{\sqrt{1-\varepsilon^2}}\right)\sqrt{\frac{m_2}{m_o}}\left[\int_0^{\infty}\int_{\alpha\left(\frac{\bar{T}_m}{\sqrt{m_o}}\right)^2\lambda^2}^{\infty}\left\{p_I^2\, f_I(\nu,\lambda) + p_{II}\, f_{II}(\nu,\lambda)\right\} d\nu\, d\lambda\right] T_h \times (60)^2$$

$$(13)$$

NUMERICAL EXAMPLE OF IMPACT PRESSURE

As an example of the application of the prediction method developed in the previous sections, numerical computations were carried out using the wave spectrum shown in Figure 6. The spectrum was obtained from data measured in the North Atlantic and its significant wave height is 10.8 meters (35.4 feet). Figure 7 shows the probability density function of breaking wave periods computed by Equation (8). The modal value of the density function is $\lambda = 0.86$ which implies that waves with period of approximately 6.2 sec. have the highest probability of breaking in this sea.

The probability density function of impact pressure at the front face of a circular cylinder associated with breaking waves for the spectrum given in Figure 6 is shown in Figure 8, while the probability density function of extreme pressure in 50 breaking waves is shown in Figure 9. The probability density functions are computed for both breaking and broken wave impacts. As can be seen in these figures, there is no significant difference in the probability density functions for breaking and broken wave impacts. The magnitude of impact pressure is most likely to occur in this sea is on the order of 1.5 kg/cm^2, while the magnitude of the most probable extreme impact pressure in 50 breaking waves is approximately 2.9 kg/cm^2.

Figure 10 shows the probable extreme impact pressure as a function of time. Included also in the figure is information on the number of breaking waves. It can be seen that the magnitude of probable extreme pressure increases sharply for the first one-

half hour, then thereafter increases slowly with time in this sea. It is expected that a structure may encounter a total of 65 breaking waves in one-hour in this sea, and the magnitude of the extreme impact pressure may reach 3.0 kg/cm^2 once during this time period. The magnitude of probable extreme impact pressure will not increase substantially after one-hour as long as the sea severity (significant wave height) remains steady.

CONCLUSIONS

This paper presents a method to statistically predict the magnitude of impact pressure (including extreme values) produced by deep water wave breaking on a circular cylinder representing a column of an ocean structure. The probability density function of wave period associated with breaking waves is derived for a specified wave spectrum, and then converted to the probability density function of impact pressure. Impacts caused by two different breaking conditions are considered; one is the impact associated with waves breaking in close proximity to the column (breaking wave impact), the other is an impact caused by waves approaching the column after they have broken (broken wave impact).

As an example of the application of the present method, numerical computations were carried out for a wave spectrum of significant wave height 10.8 m (35.4 ft) obtained from measured data in the North Atlantic. The results show that there is no

significant difference in the probability functions for breaking and broken wave impacts, and that the magnitude of extreme impact pressure increases sharply for the first one-half hour then thereafter increases slowly with time in this sea.

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APPENDIX I: EXPERIMENTS ON HYDRODYNAMIC IMPACT CAUSED BY BREAKING WAVES

In order to obtain the fundamental relationship between pressure, wave particle velocity, and wave celerity at the instant breaking waves impact a column, an experimental study was carried out in the 40-meter long wave tank at the University of Florida. The functional relationships are necessary in order to derive the probability density function of impact pressure from knowledge of the probability density function of wave period.

A circular cylinder with a 10.2 cm (4 inch)-diameter was installed at the center-line of the tank (see Figure 11). A pressure transducer which has a diameter of 0.64 cm (1/4 inch) and a natural frequency of 54k Hz was installed on the front face of the cylinder.

Breaking waves used in this experimental study were generated by a method called "Traveling Wave Fronts" proposed by Longuet-Higgins (1974) in which breaking waves were generated by a sudden start of the wave-maker. Longuet-Higgins showed theoretically that with this technique the envelop function of wave amplitude at first increases exponentially and then overshoots by approximately 19 percent before settling down to its final amplitude. Hence, it is possible for waves to attain their breaking amplitude if an appropriate combination of frequency and amplitude is assigned to the wave-maker.

In chis series of experiments, the following were measured:

- Impact pressure on the cylinder at the level of the breaking wave crest
- Horizontal fluid particle velocity at the instant of impact
- Breaking wave celerity, and
- Wave surface elevation

In order to determine whether or not the pressure transducer was at the level of the wave crest when impact occurred, three capacitance-type wave gages were installed to measure the wave surface elevation. Gauge No. 1 shown in Figure 11 was located 15.3 cm to the left (facing the cylinder) of the center of the cylinder, and Gauges No. 2 and No. 3 were located 20.3 cm and 11.7 cm, respectively, to the right (facing the cylinder). Gauge No. 3 was used as a supplemental check. From the measured height of the crests on Gauges No. 1 and No. 2, the crest height at the front face of the cylinder was determined.

The horizontal fluid particle velocity at impact was measured by using a small nylon particle, a stroboscope and a camera. The camera not only recorded the stroboscopic images of the nylon particles, but also the stroboscopic images of the breaking wave crest. The celerity of breaking waves was determined from the latter recording.

Records from the pressure transducer showed a sudden increase in pressure of short duration at the instant the cyclinder encountered the breaking waves followed by another pressure increase due to the passage of the breaking waves. There was no distinct difference in the time histories of the impact pressure

for the two different types of impact associated with breaking waves; namely, the breaking wave impact and the broken wave impact. The time duration of both types of impact was on the order of 0.05 seconds. Figure 12(a) and (b) show examples of pressure records for breaking wave impacts, while Figures 12 (c) and (d) show those for broken wave impacts. Included also in the figures are the wave surface elevations recorded by Gauges No. 1 and No. 2.

APPENDIX II: JOINT PROBABILITY DENSITY FUNCTIONS FOR TYPE I AND TYPE II EXCURSIONS

The joint probability density function of Type I excursion defined in Figure 4 (CA in Figure 4) and the associated time interval, T, is essentialy the same as that for the positive maxima, A, and the associated time interval, which was derived by researchers at the Centre National Pour L'Exploitation des Oceans (CNEXO) (Arhan et al. 1976). By considering twice the magnitude of the positive maxima, the joint probability desnity function associated with Type I excursion can be written in dimensionless form as follows:

$$f_I(\nu, \lambda) = \frac{1}{32\sqrt{2\pi}} \frac{\left(1+\sqrt{1-\varepsilon^2}\right)^3}{\varepsilon(1-\varepsilon^2)} \frac{\nu^2}{\lambda^5}$$

$$\times e^{-\frac{\nu^2}{8\varepsilon^2\lambda^4}\left\{\frac{1}{16}\frac{\left(1+\sqrt{1-\varepsilon^2}\right)^4}{1-\varepsilon^2} - \frac{1}{2}\left(1+\sqrt{1-\varepsilon^2}\right)^2\lambda^2 + \lambda^4\right\}}$$

$$0 \leqq \nu < \infty \qquad 0 \leqq \lambda < \infty \tag{14}$$

where, ν = dimensionless positive maxima (double amplitude), $\zeta/\sqrt{m}$.

with $\zeta = 2\zeta_A$

ζ_A = magnitude of the positive maxima

m_o = area under the spectral density function

The joint probability density function of Type II excursion and the associated time interval is given in dimensionless form as follows (Ochi and Tsai 1983):

$$f_{II}(\nu, \lambda) = \frac{k(\varepsilon)}{16\sqrt{\pi}} \; \frac{\left(1 + \sqrt{1-\varepsilon^2}\right)^5}{\varepsilon(1-\varepsilon^2)\left(\varepsilon^2 + 2\sqrt{1-\varepsilon^2}\right)} \; \frac{\nu^2}{\lambda^5}$$

$$\times \; \exp\left\{-\frac{\nu^2}{2\varepsilon^2}\left(\left\{1 - \beta(\varepsilon, \lambda)\right\}^2 + \left\{\frac{\varepsilon}{8} \; \frac{\left(1+\sqrt{1-\varepsilon^2}\right)^2}{\sqrt{1-\varepsilon^2}} \; \frac{1}{\lambda^2}\right\}^2\right)\right\}$$

$$\times \left[\begin{array}{l} \exp\left\{\dfrac{\lambda^2}{4\varepsilon^2}\left(1 - \beta(\varepsilon, \lambda)\right)^2\right\} \cdot \left\{1 - \Phi\left(\dfrac{\nu}{\sqrt{2}\varepsilon}\left\{1 + \beta(\varepsilon, \lambda)\right\}\right)\right\} \\[2ex] + \dfrac{\sqrt{2(1-\varepsilon^2)}}{1+\varepsilon^2} \; \exp\left\{\dfrac{\nu^2}{2\varepsilon^2}\left((1-\varepsilon^2) - 2\beta(\varepsilon, \lambda)\right)\right\} \\[2ex] + \dfrac{2\sqrt{\pi}\sqrt{1-\varepsilon^2}}{\varepsilon(1+\varepsilon^2)^{3/2}} \; \nu\left\{1 - \beta(\varepsilon, \lambda)\right\} \cdot \exp\left\{\dfrac{\nu^2}{2(1+\varepsilon^2)\varepsilon^2}\left(1 - \beta(\varepsilon, \lambda)\right)\right\} \\[2ex] \qquad \times \left\{1 - \Phi\left(\dfrac{\nu}{\varepsilon\sqrt{1+\varepsilon^2}}\left\{\varepsilon^2 + \beta(\varepsilon, \lambda)\right\}\right)\right\} \end{array} \right]$$

$$0 \leqq \nu < \infty, \quad 0 \leqq \lambda < \infty \tag{15}$$

where, $\nu = \zeta / \sqrt{m_0}$ with $\zeta = \xi_A - \xi_B$

ξ_B = magnitude of the positive minima

$$\beta(\varepsilon, \lambda) = \left(\frac{1 + \sqrt{1-\varepsilon^2}}{2\sqrt{2}} \; \frac{1}{\lambda}\right)^2$$

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NOMENCLATURE

C_*	wave celerity associated with wave breaking
$f(\ )$	probability density function
$f_*(\lambda)$	probability density function of breaking wave period (dimensionless form)
f_I	joint probability density function of positive maxima (double amplitude) and associated time interval including that applicable to Type I excursion
f_{II}	joint probability density function of excursion (height) and associated time interval (period) of Type II excursion
$F(\ )$	cumulative distribution function
g	gravity constant

$g(\ )$	probability density function of extreme values
k	constant associated with impact pressure
m_j	j-th moment of the wave spectral density function
p	impact pressure
p_I	frequency of occurrence of Type I excursion
p_{II}	frequency of occurrence of Type II excursion
T	time interval between positive maxima or period
T_h	time in hours
$\overline{T}_m$	average time interval between successive positive maxima
U	wave particle velocity at the instant of breaking wave impacts a structure
α	constant associated with wave breaking criterion
ϵ	band-width parameter of the spectrum
ζ	excursion
ζ_A	magnitude of positive maxima
ζ_B	magnitude of positive minima
θ	constant associated with impact velocity
λ	dimensionless time interval between positive maxima (dimensionless wave period), $T/\overline{T}_m$
ν	dimensionless excursion (dimensionless wave height), $\zeta/\sqrt{m_o}$

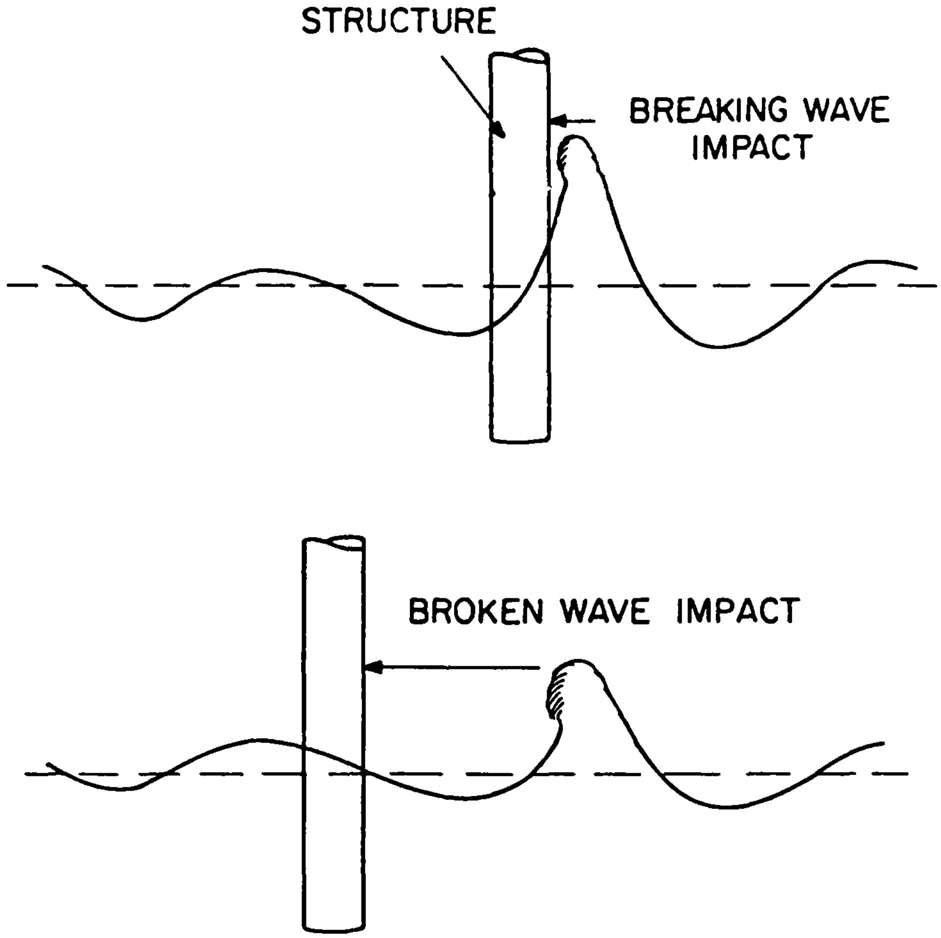


Figure 1 Pictorial sketch indicating breaking wave impact and broken wave impact

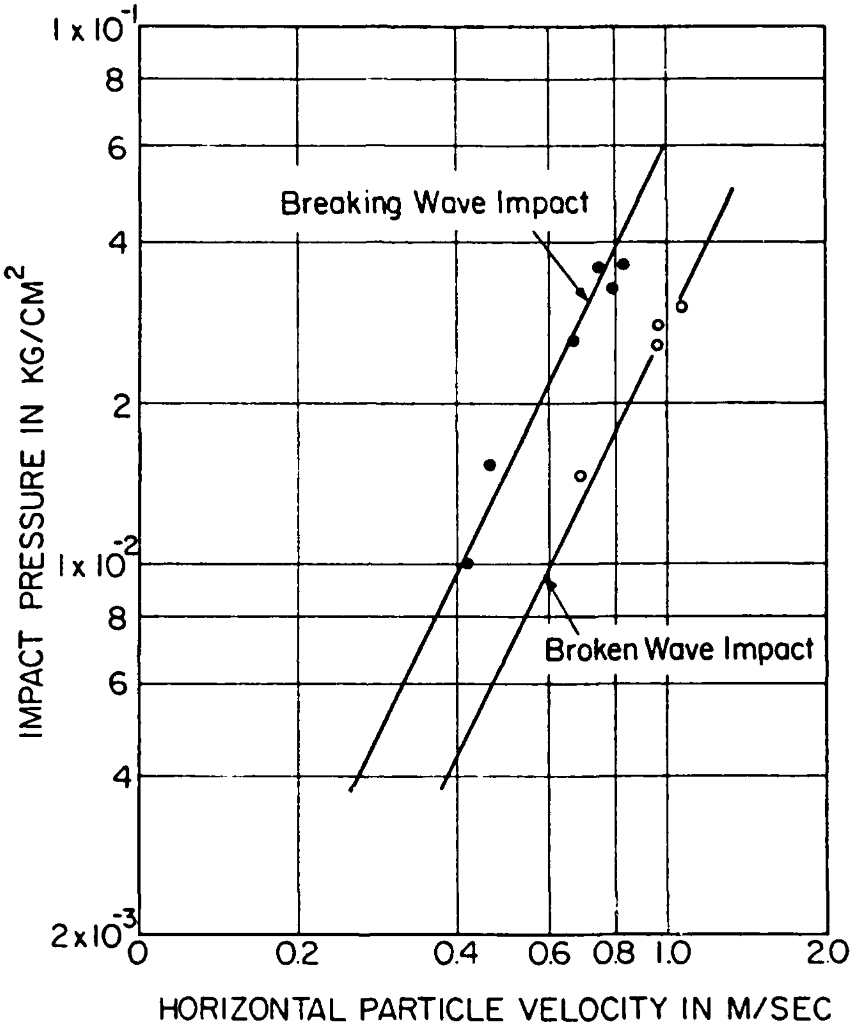


Figure 2 Impact pressure associated with wave breaking as a function of wave particle velocity at the instant of impact

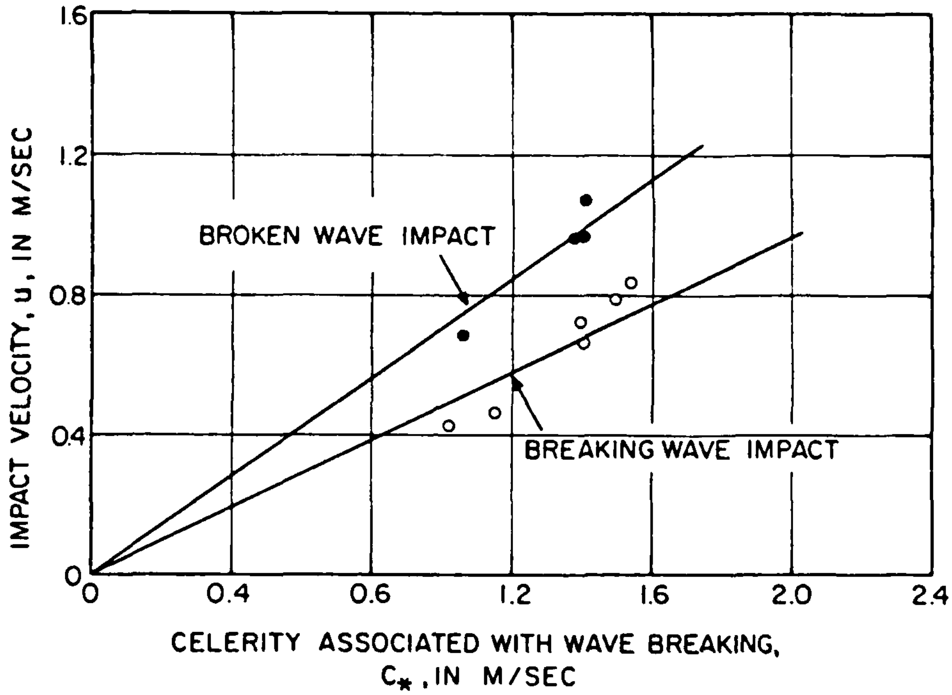


Figure 3 Impact wave particle velocity as a function of celerity (phase velocity) associated with wave breaking

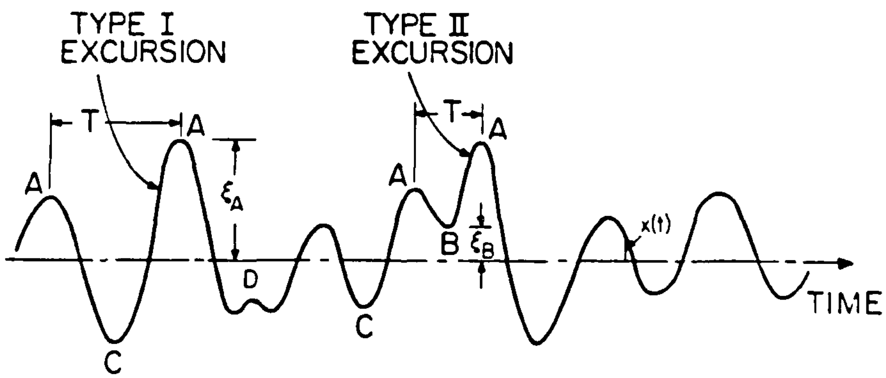


Figure 4 Explanatory sketch of non-narrow-band random process

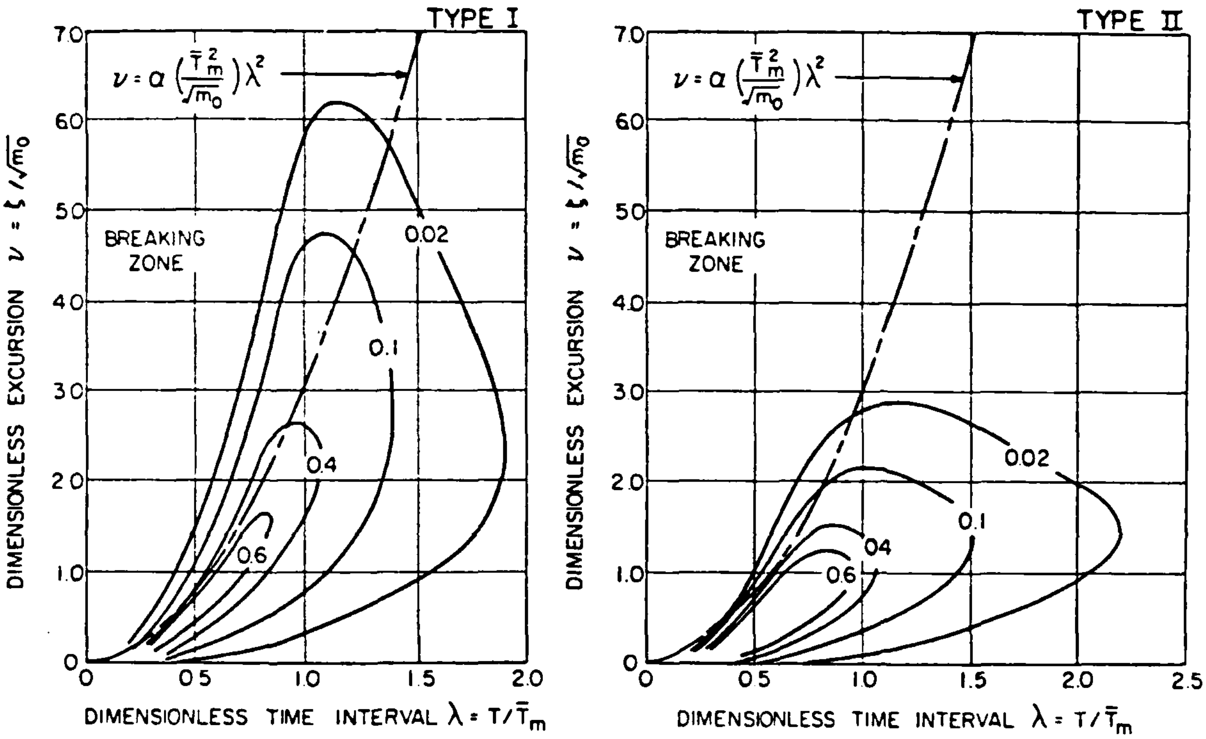


Figure 5 Joint probability density function of the excursion and time interval for Type I and Type II excursions

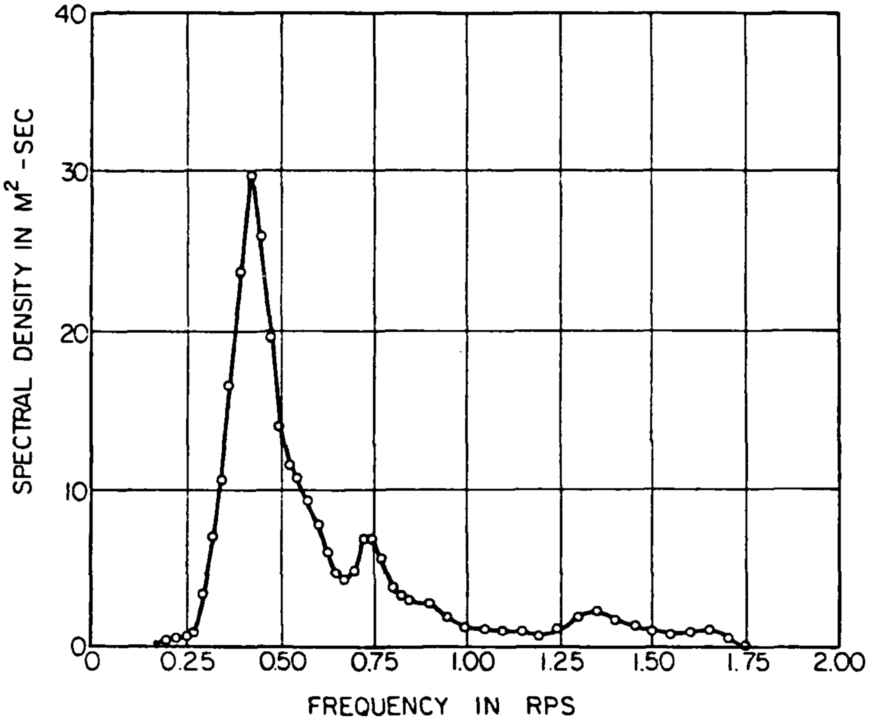


Figure 6 Spectral density function of significant wave height 10.8 m (35.4 ft.) measured in the North Atlantic

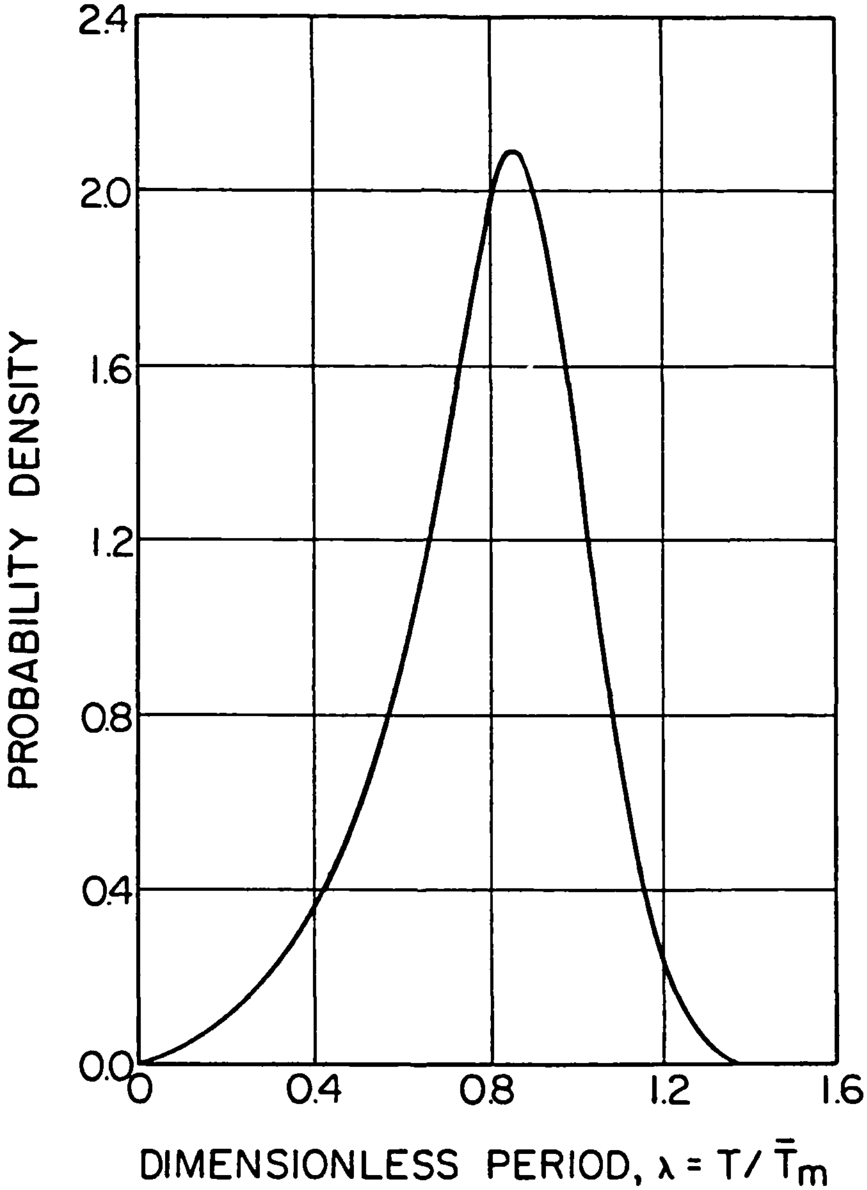


Figure 7 Probability density function of breaking wave periods

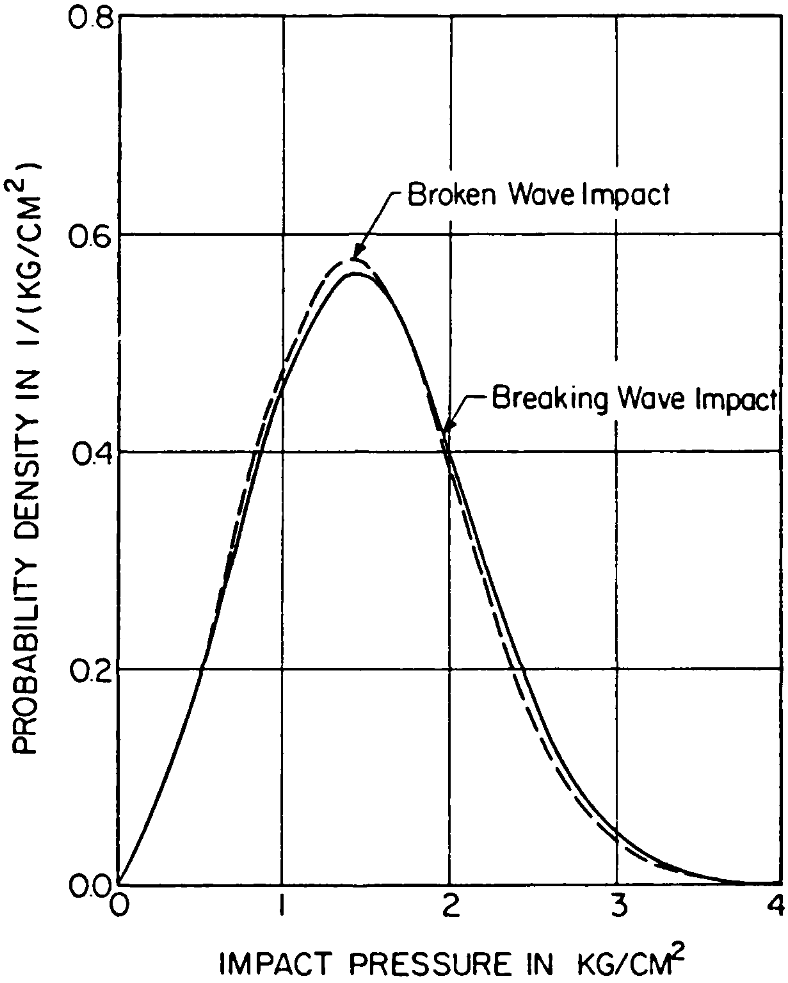


Figure 8 Probability density functio of impact pressure at the front face of a circular cylinder in a sea of significant wave height 10.8 m (35.4 ft.)

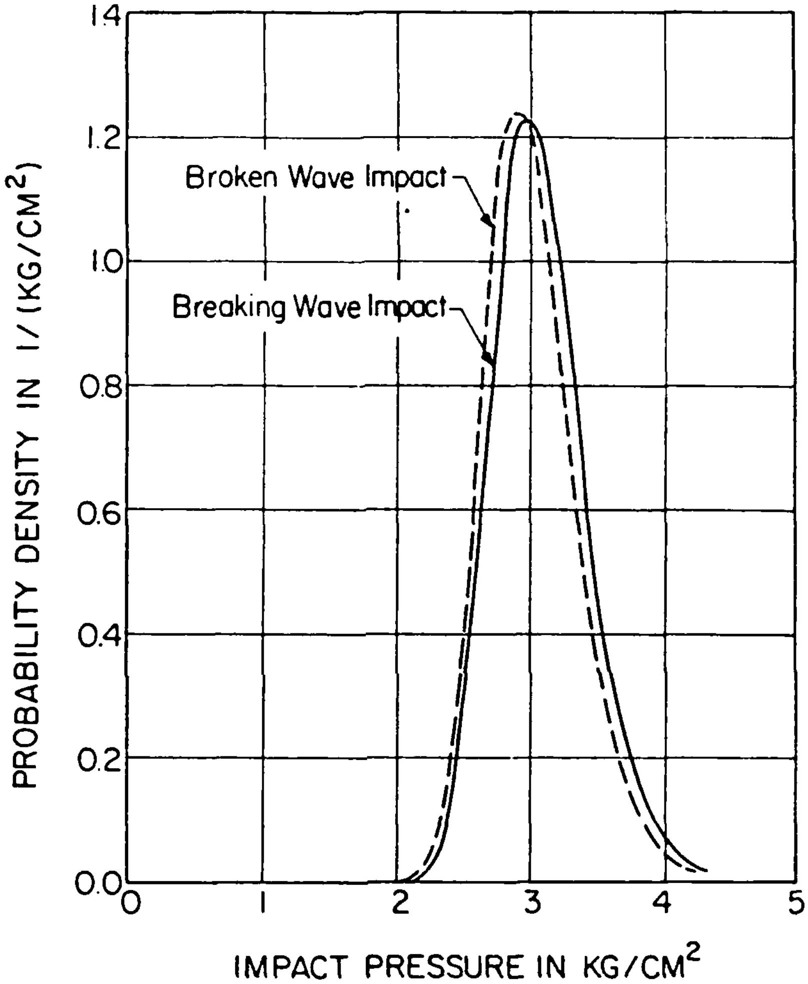


Figure 9 Probability density function of extreme impact pressure in 50 breaking waves in a sea of significant wave height 10.8 m (35.4 ft.)

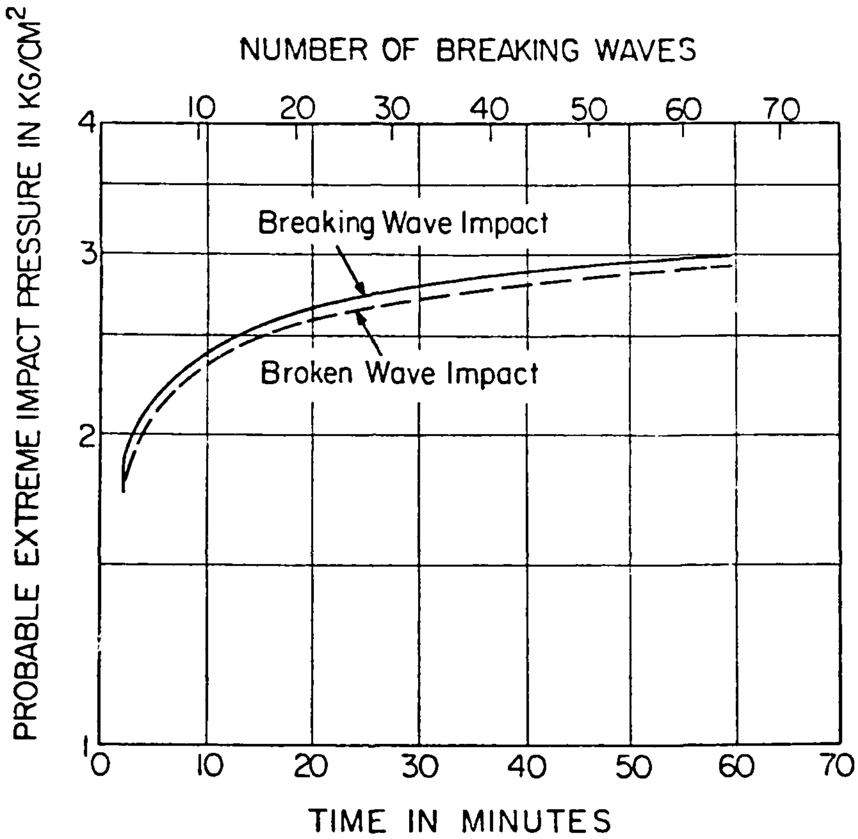


Figure 10 Magnitude of probable extreme impact pressure as a function of time in a sea of significant wave height 10.8 m (35.4 ft.)

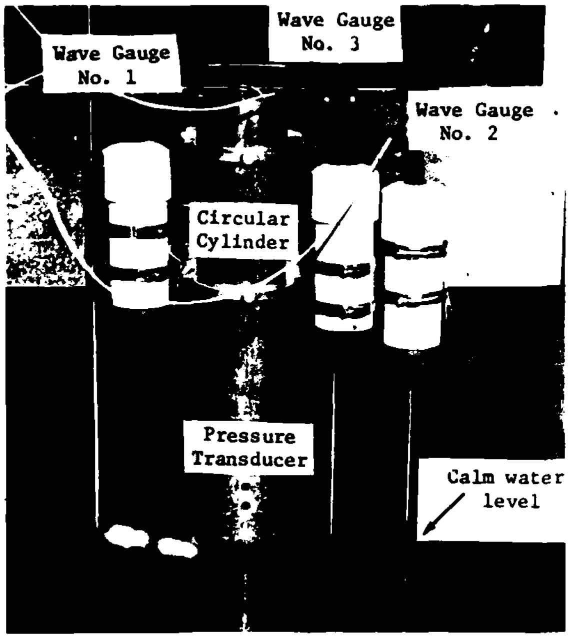


Figure 10 Set-up of cylinder and wave gages for experiments on impact associated with wave breaking

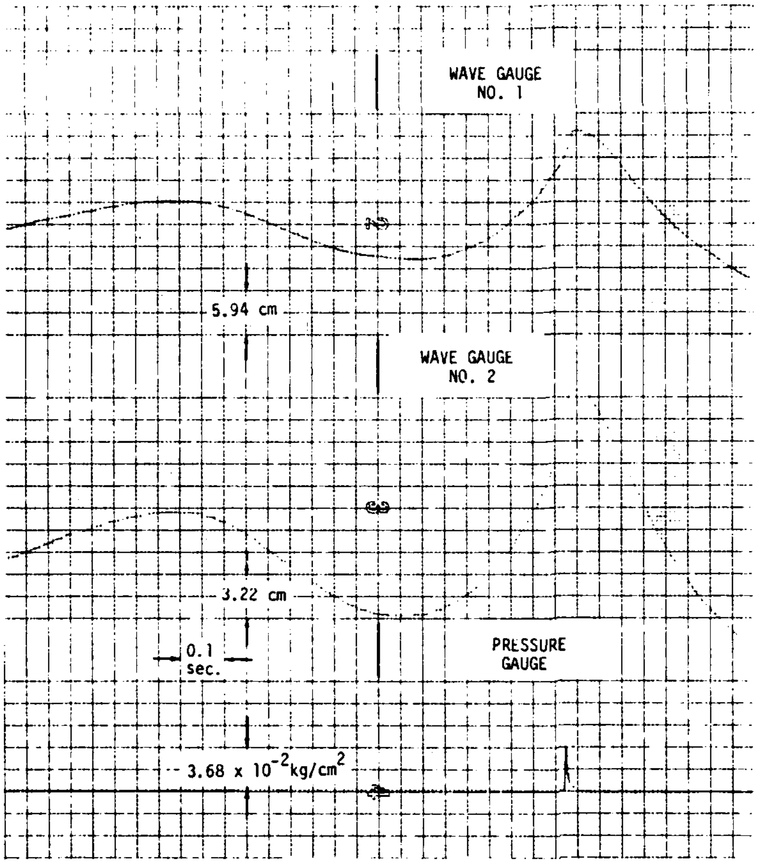
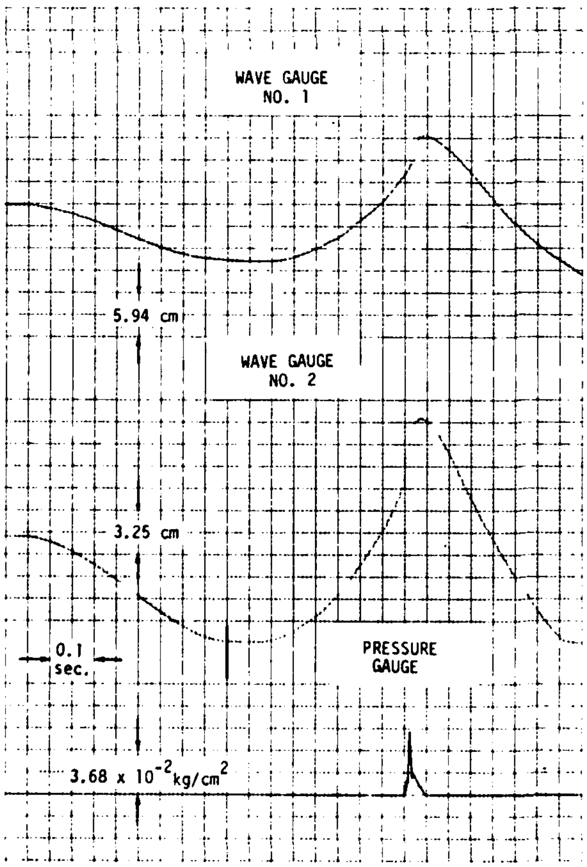
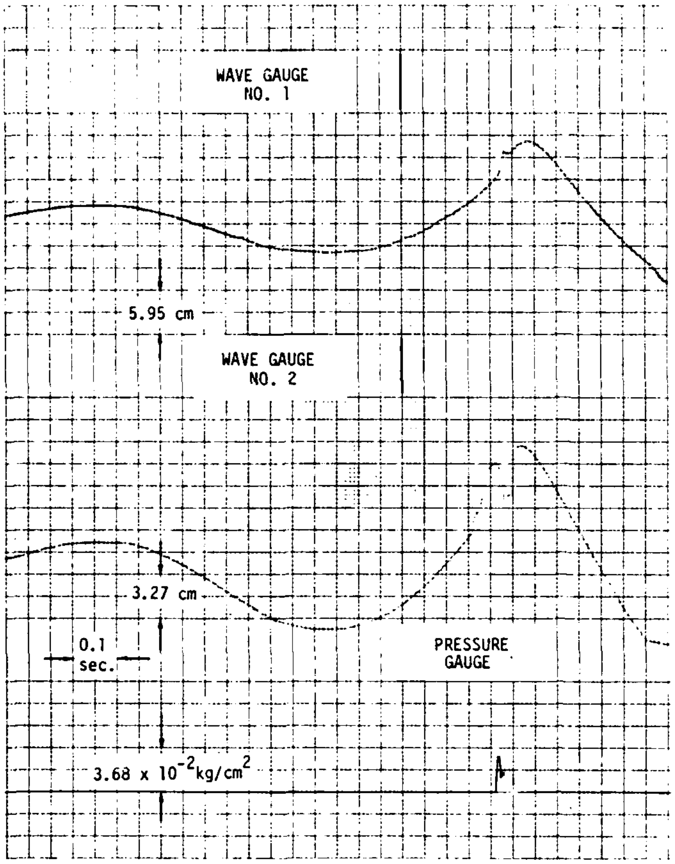


Figure 12
Examples of wave surface elevation and pressure measured during tests

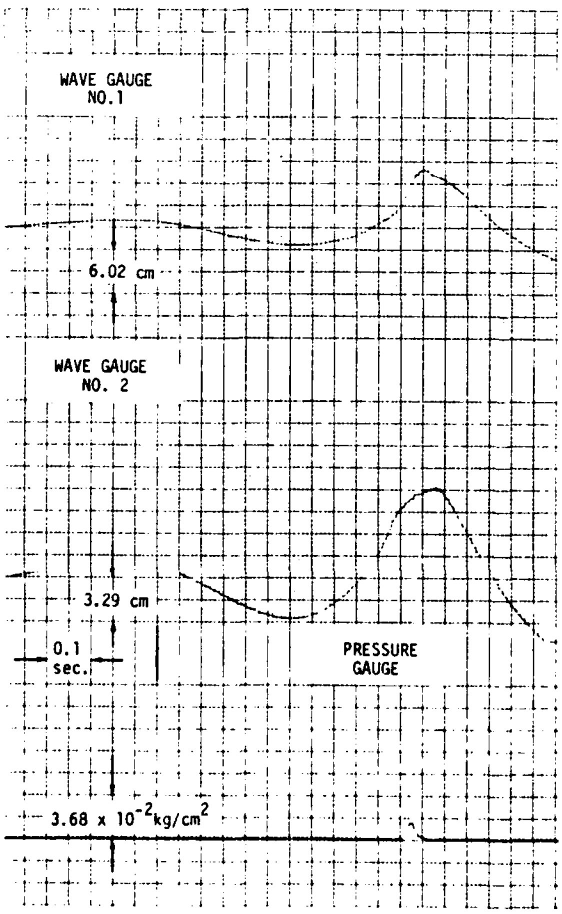
(a) Breaking wave impact



(b) Breaking wave impact



(c) Broken wave impact



(d) Broken wave impact

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